Contributions to Geophysics and Geodesy Vol. 37/2, 2007

# Energy balance measurements in an urban park in tropical city Delhi (India)

Y. Das
Centre for Atmospheric Sciences, Indian Institute of Technology Delhi[1]

B. Padmanabhamurty
School of Environmental Sciences, Jawaharlal Nehru University[2]

Abstract: Energy balance measurements were carried out in an urban vegetated area of Delhi. These measurements were made on several days during winter (November, December, January, February) and summer (April, May, June) of 1998 and 1999, respectively. Net radiation ($Q^*$) and soil heat flux (G) were directly measured. Sensible heat flux (H) and latent heat flux (LE) were calculated from Bulk-aerodynamic approach and results are presented based on the analysis of energy balance components. Diurnal pattern of $Q^*$ shows pronounced variation indicating higher values during summers as compared to winters. $Q^*$ reached as high as 327.43 W/m$^2$ during midday hours of summer 1999, whereas, it was about 100 W/m$^2$ during winter 1998. $Q^*$ dissipated by 38% and 62% by H and LE during winter 1998, and the apportionment of H and LE accounted for about 34% and 51%, respectively during 1999. Nevertheless, 60% and 54% of $Q^*$ is utilized in heating the air of the lower atmosphere, compared to the 23% and 27% of $Q^*$ that is expended in evaporation in summer 1998 and 1999, respectively. On an average for all the seasons, daily total sum of energy fluxes is higher than net radiation by about 12.55 W/m$^2$ indicating the deficit of energy during the study period. Probably, diurnal variation and seasonal differences in energy balance components are due to the nature of the substratum, plant phenology and local conditions which influence the energy partitioning. The calculated Bowen ratio and normalized energy balance components, when compared with other sites, support the hypothesis that the present study site is similar to the rural/vegetated area during winter season, but to an urban site during summer season. However, as there was no surplus of energy the area acts as a heat sink in both the seasons.

**Key words:** energy balance, vegetated area, latent heat flux, sensible heat flux, soil heat flux

---

[1] Haus Khas, New Delhi - 110 016, India; e-mail: yashvantdas@hotmail.com

[2] B-3B/8C, Janakpuri, New Delhi - 110057, India

## 1. Introduction

Human activity places a stress on urban environments that green spaces and vegetation cover help relieve. Transpiring plants release water vapour to the surroundings, making the humidity increase and temperature decrease. Typical rates of heat loss by evaporation in arid environments with good irrigation range from 284.2 $W/m^2$ to 342.2 $W/m^2$, whereas in temperate climates rates range from $< 8.12$ (winter) to 85.84 $W/m^2$ (summer) *(Jones, 1992)*. The release of water vapour corresponding to these loss values ranges from 12 to 0.28 $l/m^2$ per day *(Barradas, 1991)*. Vegetation clean the air and, along with water resources, act as a moderator of climate. Urban green belts and large expanses of preserved open space also facilitate significant groundwater recharge. Vegetal cover acts as a pollution scavenger or pollution sink, as it absorbs gases and gathers particulate matter through leaves. The green and leafy portions of the trees and plants have the capacity to filter dust, smoke and other pollutants in the air. A 0.01 $km^2$ of woodland (about 1000 trees) absorbs 3.7 tonnes of $CO_2$ from the atmosphere and gives out 2.5 tonnes of life – sustaining $O_2$. A full grown *Ficus-religiosa* (Peepal) tree is, for instance, estimated to give out 600 kg of $O_2$ per day *(Greening Delhi Action Plan, 2005-2006)*.

Therefore, urban vegetation play an important role in urban climate because of their capacity to absorb solar radiation and heat. They dissipate this energy load via latent heating rather than sensible heating *(Barradas et al., 1999)*. Urban vegetated areas thus become small islands which are cooler and more humid, and produce into a hotter and drier environment an urban mosaic of microclimate. This effect of increasing humidity and decreasing temperature of vegetation also changes thermal comfort indices, making city parks more comfortable compared to surrounding urban environment *(Barradas, 1991)*. They act as an oasis, and are cooler and more humid than their surroundings. The presence of vegetation in cities ameliorates the heat load and makes the areas/city climate thermally comfortable *(Oke, 1987)*. It can bring a significant difference in heat and radiation balance by causing local climatic effect in cities *(Thorsson and Eliassons, 2003)*. City parks act as heat/pollution sinks and are of immense importance in radiation/energy balance studies in the urban ecosystem *(Padmanabhamurty, 1999a; 1999b)*. The thermal bioclimatic conditions and patterns of behavior in an urban park and the effect of green areas in urban ecosystem in Gotenborg, Sweden has been extensively investigated *(Upmanis et al., 1998; Upmanis, 1999; Thorsson et al., 2004)*. The surface energy balance and climate in an urban park (Humlegarden located in central Stockholm) and its surroundings has been studied by *Backstrom (2006)*. In India field experiments such as Vegetation and Surface Energy Balance Experiment (VEBEX) in Bangalore *(Raman et al., 1998)* and Land Surface Processes Experiment (LASPEX) in Gujarat *(Vernekar et al., 2003)* provided unique opportunity for understanding the land-atmosphere exchange processes of energy and moisture in different surface characteristics and seasons. The European Field Experiment in a Desertification-Threatened Area (EFEDA) *(Bolle et al., 1993)* and Flux Network (FLUXNET) field campaign *(Baldocchi et al., 2002; Wilson et al., 2002)* provides a comprehensive land surface dataset and unique contribution to the study of the environmental, biological and climatological controls of net surface exchanges between vegetation and the atmosphere in contrasting ecosystem and climates. Some advanced experimental field campaigns with international flavour in this field, cf. the Basel Urban Boundary Layer Experiment (BUBBLE) *(Rotach, 2002; 2005)* and the Experiments to Constrain Models of Atmospheric Pollution and Transport of Emissions/Urban Boundary Layer-Couche Limite Urbaine (ESCOMPTE/UBL-CLU) at Marseille *(Cros et al., 2004; Mestayer et al., 2005)* are noteworthy in urban ecosystem research. Such campaigns are characterized by multiple sub-investigations with methodologies which cut across scales and provide unique contributions to physical environment and urban ecosystem investigations *(Grimmond, 2006)*. *Lemonsu et al. (2004)* evaluated the performance of the Town Energy Balance (TEB) model with Interactions between Soil, Biosphere, and Atmosphere (ISBA) scheme using the ESCOMPTE/CLU-UBL observational datasets. *Lagouarde et al. (2006)* used new technology (large aperture Scintillometry) for measuring sensible heat flux at Marseille. Studies on Heat fluxes and stability in cities and urban–rural energy balance differences were carried out by *Grimmond and Oke (2002)*. Suburban–rural energy balance comparisons in summer for Vancouver, B. C. by *Cleugh and Oke (1986)*, the surface energy balance in urban areas by *Piringer et al. (2002)*, spectral characteristics and correction of long-term eddy covariance measurements over two mixed hardwood forests in non-flat terrain by *Su et al. (2004)*, heat storage and energy balance fluxes for a forested area by *McCaughey and Saxton (1988)*, and the energy balance studies in the vegetated area by *Oliphant et al. (2004)* are well documented. *Offerle et al. (2006)* studied the temporal variations in heat fluxes over a central European city centre and indicated the role of vegetation and anthropogenic heat input in average daily daytime energy balance components and Bowen ratio variability. *Jochum et al. (2005)* and *Cao and Ma (2004)* studied the characteristics of energy balance components in different vegetation types and land use classification using different methods. The surface energy balance in an irrigated urban park in suburban Sacramento, California has been carried out by *Spronken-Smith, Oke and Lowry (2000)*. They directly measured the fluxes of net radiation, soil heat flux and evaporation at each site and evaluated the convective sensible heat flux by residual method. Strong advective effects on evaporation are reported, especially in the afternoon and evening. The driving forces they attributed for this are the differences in surface and air temperature, and humidity, between the cool, wet park and its warmer, drier built-up surroundings.

Delhi is the national capital of India. Its geographic area is 1483 km$^2$ of which 11.46% (170 km$^2$) is forest cover, which comprises of 52 km$^2$ of dense forest and 118 km$^2$ of open forest. The extent of scrub is 1 km$^2$. Forest Survey of India (Ministry of Environment and Forest), in their recent survey based on satellite data concluded that green areas over Delhi are increasing due to plantation, soil conservation and check of deforestation (MoEF, 1999; FSI, 2003). Some of the vegetated areas of city are Deer Park (1.61 km$^2$), Gandhi Darshan (1.76 km$^2$), Asolabhatti Park (27.81 km$^2$) and Buddha Jayanti Park (BJP) (61.97 km$^2$) etc. Delhi City is in continuous expansion, due to influx of migrants; developmental works, construction activities etc., which continuously modify the land-use of the regions. At present the population of Delhi is about 16 million. The rate of increase of population is 4.27% per annum. It is expected that the Annual projected population of Delhi up to 2026 will be about 28 million as estimated by the office of the Registrar of General India on the basis of 2001 population census *(Census of India, 2001; Delhi Development Report, 2006)*. Cities with more than 10 million inhabitants have their own climate and hence changes in radiation energy and moisture balances *(Oke et al., 1999)*.

In the last 2 decades a number of energy balance studies were carried out over cities, but there is still a lack of knowledge on exchange processes and energy partitioning over dense urban surface and city parks *(Christen et al., 2002; Backstrom, 2006).* It is therefore important to investigate the physical features that produce this local climate changes through the energy balance *(Budyko, 1981).* Within the cities the net uptake or release of energy by latent and sensible heat flux changes with different land uses *(Oke et al., 1992).* Despite the importance of city parks or vegetated areas in city climate, there is a lack of studies on the role of vegetation in tropical urban ecosystem *(Barradas et al., 1999).*

This paper presents the energy balance over a vegetated area in tropical city Delhi. The study was carried out in a vegetated area, southern ridge (BJP), a city where radiation/energy and water balance studies, microclimatic, heat island, thermal comfort studies etc. have been extensively carried out *(Padmanabhamurty, 1984; 1990; 1990/91; 1994a; 1994b; 1999a; 1999b).*

The objective of this study is to investigate the energy balance of an urban vegetated area to identify the heat/pollution sinks and to understand the resulting thermal and moisture regimes, which contribute to the knowledge of the physical urban environment in a tropical city for human comforts.

## 2. Study site

Energy balance studies were carried out over BJP (lat. 28°30′ N, long. 76°50′ E). It lies in one of the prime areas of the city of Delhi, in the west of Rajpath, and is considered to be a significant and precious part of the environmental heritage of the capital. The park covers the major portion of the southern ridge, with an area of 61.97 $\mathrm{km}^2$ including Dhaula Kuan landscape area. It is a part of the Delhi Ridge (Delhi ridge is divided into four zones, namely the southern ridge, the south central ridge, the central or the new ridge, and the northern or the Old Delhi ridge), an extension of the Aravalli mountains acts as the green lung of the city; maintained by Delhi Development Authority (DDA) and Sports Authority of India (SAI) *(Greening Delhi Action Plan, 2005-2006)* (Fig. 1, Map of Delhi, Locating BJP as shown in Fig. 1).

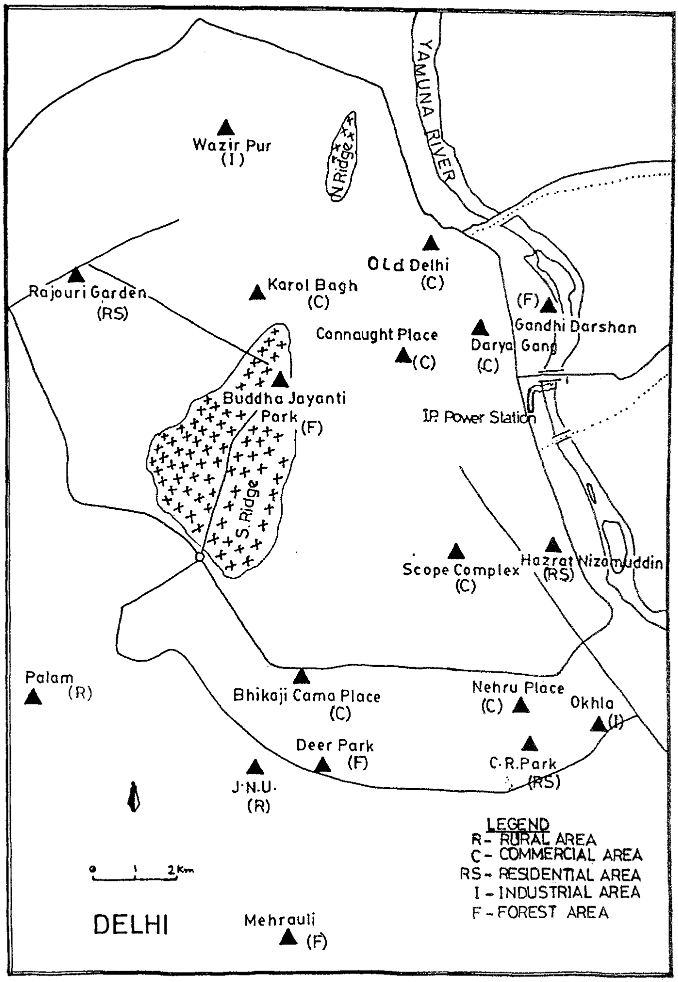

Fig. 1. Map of Delhi locating Buddha Jayanti Park (BJP).

The climate of the Delhi region is semiarid type, with three well defined seasons. The average annual rainfall of the area is 625 mm, of which 95% occurs during the monsoon season (July to September). On an average, rain of 2.5 mm or more falls on 27 days in a year. Of these, 21.4 days are during monsoon months. The cold season begins at the end of November, and extends to the late February. The hot summer extends from the end of

March to the end of June. The temperature is usually between 21.1°C to 40.5°C during these months. Winters are usually cold and night temperatures often fall to 6.5°C during the period between December and February. Predominant wind direction is generally W-NW but during monsoon E-SE, with a range of average speed varying from 2.5 to 3 $\mathrm{ms}^{-1}$. The average annual temperature recorded in Delhi is 31.5°C based on the records over the period of 70 years maintained by the Meteorological Department (India Meteorological Department, New Delhi, 1998).

Southern ridge part of Delhi is rocky with dissected land. According to soil classification of National Beauro of Soil Survey and Land Use Planning, Nagpur (ICAR); the soil of this region falls under aquents-fluvents. The water table ranges from 10-20 m below ground level. The soils of the Delhi area are mostly light with subordinate amount of medium texture soils. The light texture soils are represented by sandy, loamy, sand and sandy loam; whereas medium texture soils are represented by loam silty loam (CSE Report).

Vegetation are mainly of tropical dry deciduous types. The native Aravali species of plants like *Anogeissus pendula* (Dhoy), *Acasia arbica* (Babul), *Jujube* (Ber) etc. are found. The average shrub heights are 1.5 m with some isolated small trees of around 5.0 m height. However, some *Eucalyptus sp.* and *Sagwan* varieties of trees (approximate height of 20 m) including *Azadirachta indica* (Neem), *Cassia-fistula* (Amaltas), *Eugenia jambolana* (Jamun), *Ficus-religiosa* (Peepal), *Terminalia arjuna* (Arjun), *Dalbergia-sisoo* (Gulmohur) and *Kigelia pinnata* (Sausage) have also been planted surrounding the Park *(Greening Delhi Action Plan, 2005-2006).* During morning and evening hours the garden is irrigated. Adjacent to the park there is a tar road (Ridge Road or Sardar Patel Marg, opposite Assam House) with busy traffic during 10:00 am and 05:00 pm.

## 3. Materials and methods

Energy balance measurements were made over vegetated areas (BJP) of Delhi on several days during winter (November, December, January, February) and summer (April, May, June) of 1998 and 1999, respectively. This experimental campaign was part of a project sponsored by the Ministry of

Science and Technology, Government of India (No. ES/048/319/95), aimed at acquiring experimental data for defining the micrometeorology of urban ecosystem of the tropical city Delhi, according to different land use pattern *(Padmanabhamurty, 1999a, 1999b; Das, 2002).*

Net radiation (Q*) was measured with the help of Net radiometer (Swissteco, Type S-1) with two replaceable plastic domes and a collapsible stand, which can be adjusted to desired height. The spectral range was 0.3 to $100\mu$m with direct output voltage of 1 Mv corresponding to 66.6 $W/m^2$. A soil heat flux plate (HFT-3, Campbell Scientific, Inc.) was used to measure the soil heat flux (G). The output voltage corresponded to 1 Mv = 60.6 $W/m^2$. Wind speed (with ± 5% error) and dry and wet-bulb temperatures (with an accuracy of 0.01°C) were measured at two heights (0.5 and 3.0 m) using a portable mast of 3.5 m height. Net radiometer and wind speed sensors were mounted separately. Net radiometer was erected at the height of 1.5 m from ground on a flat surface. Precautions were taken in installing the instruments to avoid the shadows of trees and other installations.

Hourly observations were taken and later on averaged for daily basis for analysis at the same time outlier tests also done, following *Hakansson and Peters (1995)*, to identify the values that were divergent relative to mean. The data were plotted in so called Scatter plots which provide a good overview and allows individual outliers to be identified. Some outliers representing erroneous values were identified from the scatter plots and removed *(Backstrom, 2006).*

Instruments were calibrated in the Nuclear Research Laboratory of Indian Agricultural Research Institute (ICAR), New Delhi, for the consistency of the readings and accuracy of the data. They were cleaned every week during the study periods and checked simultaneously their accuracy through calibrations. The instrument errors associated with the measured terms were about 5% for net radiation and soil heat flux and 10-12% for latent heat flux (LE) and sensible heat flux (H) *(Webb et al., 1980; Munn, 1966).* LE and H were calculated from Bulk-aerodynamic approach *(Oke, 1987)*, as used by *(Padmanamhamurty, 1994a; Saxena et al., 1996; Sathapathy, 1998; Padmanamhamurty, 1999a, 1999b; Das, 2002)* details are given elsewhere.

## 4. Results and discussion

During the measurement periods wind directions were more frequent from northwest to north-north west and from west to southwest [India Meteorological Department (Safdarjung Air Port), New Delhi]. Wind speed ranged from 0.76 to 2.75 and from 2.0 to 3.2 $\mathrm{ms}^{-1}$ in the winter and summer seasons, respectively. Maximum speeds were observed during the daytime. During winter 1998, there were series of western disturbances affecting Delhi and the sky was either overcast or cloudy for most of the time, however during winter 1999 less number of western disturbances enabled clear skies. These disturbances during their travel generate strong winds, which advect energy into the system from the immediate neighborhood. However, summer seasons were mostly sunny with partial cloudy *(Padmanabhamurty, 1999a; 1999b).*

Figs. 2–5 show the energy balance in two winters (1998 and 1999) and two summers (1998 and 1999) over Delhi. Table 1 summarizes and compares the partitioning of energy balance components in BJP, with those in the urban or suburban (vegetated) area in the metropolitan area of Mexico City; Jawaharlal Nehru University (JNU) (rural/vegetated) of Delhi City and an urban area of Central European City.

Net radiation ($Q^*$) in both the winters 1998 and 1999 increased rapidly from $-8$ W/m$^2$ and $-12$ W/m$^2$ in the morning to reaching at about 100 W/m$^2$ and 280 W/m$^2$, respectively around noon. In the afternoon $Q^*$ decreases gradually and attains minimum around 19:00 hrs in the evening. The winter 1998 showed a relatively small values of $Q^*$ during daytime. Throughout the day $Q^*$ was decreased by cloudiness in both the seasons (winter 1998 and 1999). However, drops in $Q^*$ due to cloudiness was more frequent during winter 1998. Less polluted atmosphere and lower air temperature reduces incoming long wave radiation and hence lower $Q^*$. It seems less likely that the low $Q^*$ is due to high surface albedo *(Oke et al., 1999).* During summer 1998 and 1999, at around noon (12:00-13:00 hrs) $Q^*$ was as large as 300 W/m$^2$ and 327.43 W/m$^2$, respectively in conformity with the earlier values reported by *Padmanabhamurty (1994a)* in rural/vegetated area over Delhi. Higher values of $Q^*$ was observed throughout the day during summer 1999 as compared to 1998. This could be attributed to the higher downward long wave radiation due to the cellular circulation of air between polluted

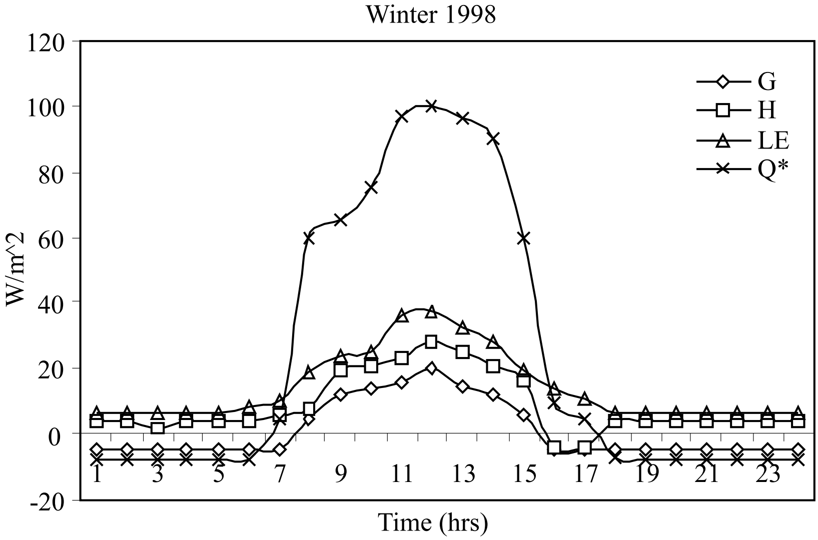

Fig. 2. Energy balance components in the Buddha Jayanti Park during winter 1998.

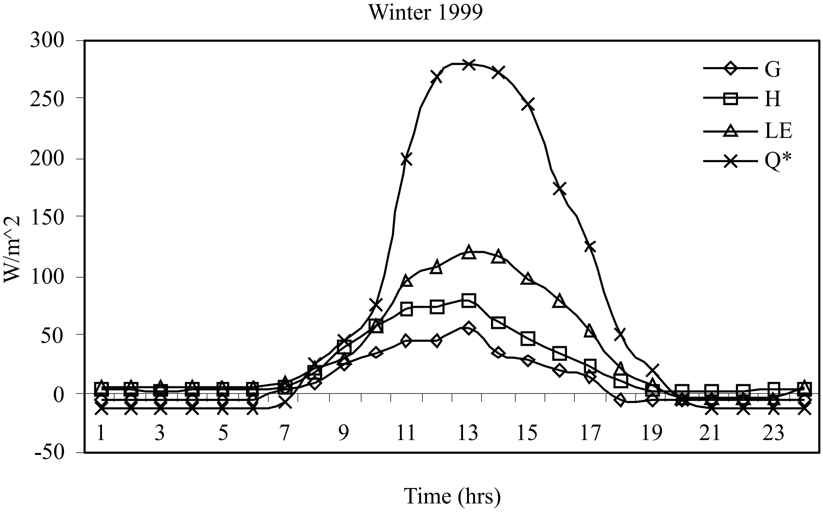

Fig. 3. Energy balance components in the Buddha Jayanti Park during winter 1999.

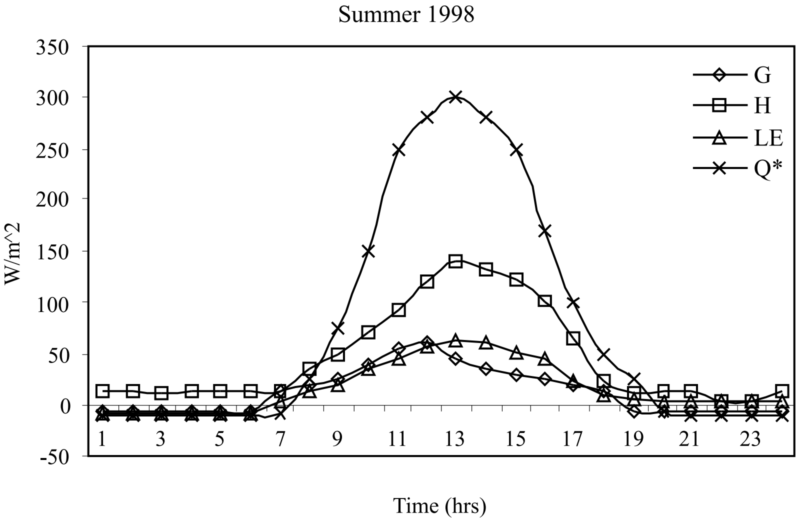

Fig. 4. Energy balance components in the Buddha Jayanti Park during summer 1998.

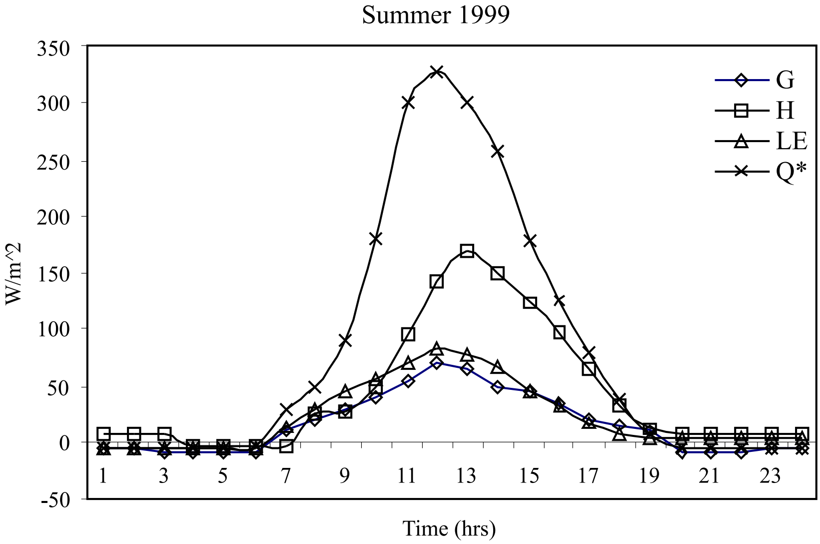

Fig. 5. Energy balance components in the Buddha Jayanti Park during summer 1999.

Table 1. Summary table for energy partitioning and comparison with different sites

| Year | 1999 | | 1998 | | 1995/1996 | | 1994 | | 1998 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Study site | BJP # | | BJP # | | University Reserve * | | JNU # | | P. School No.7* | Central European City | Central European City |
| Seasons | Winter | Summer | Winter | Summer | Dry | Wet | Summer | Winter | Dry | Wet | Wet |
| G/Q* | 0.15 | 0.20 | 0.04 | 0.18 | 0.07 | 0.03 | 0.22 | 0.17 | 0.484 | -- | -- |
| H/Q* | 0.34 | 0.54 | 0.38 | 0.60 | 0.69 | 0.27 | 0.54 | 0.31 | 0.511 | 0.52 | 0.56 |
| LE/Q* | 0.51 | 0.27 | 0.62 | 0.23 | 0.25 | 0.70 | 0.26 | 0.64 | 0.005 | 0.47 | 0.34 |
| β | 0.67 | 1.98 | 0.72 | 2.65 | 1.92 | 0.04 | 2.08 | 0.48 | 3.89 | 1.11 | 1.65 |

**Legend:**

BJP: Present study site, urban vegetated area, Delhi City

University Reserve: Suburban vegetated area, Mexico City, wet season (4th week of June and 1st week of July) *(Tejeda-Martinez and Jauregui, 2005)*, dry season (1st week of Dec.) *(Barradas et al., 1999)*.

JNU: Rural/vegetated area, Delhi City, summer (March), winter (Jan.), Reconstructed *(Padmanabhamurty, 1994a)*.

Preparatory School No. 7: Urban complex, Mexico City, dry season (1st week of Dec.) *(Tejeda-Martinez and Jauregui, 2005)*.

Central European City: Urban complex, Jun-Sept. 2001/2002 *(Offerle et al., 2006)*

#: 24-hourly values

*: day time values ($Q^* > 0$).

and warmer surroundings and vegetated areas, and almost cloudless sky enabled more global radiation *(Padmanabhamurty, 1999a, 1999b; Barradas et al., 1999)*. The duration of global radiation during winters (November, December, January, February) were shorter and in summer (April, May, June) longer, this may also be the reason for the observed behaviour of $Q^*$ in both winters and summers (Figs. 2–5).

Sensible and latent heat fluxes in the study area increased with the rise in $Q^*$ in the morning to reach their maxima around midday in both seasons. It is observed that both H and LE reached their peak at around 12:00 to 13:00 hrs in both the winters (1998 and 1999). During winter 1998, H ranged from 2.07 W/m$^2$ (morning) to $-4.21$ W/m$^2$ (evening) and around noon its value was about 28.28 W/m$^2$, whereas, during 1999, it varied from 4.14 to 78.28 W/m$^2$. LE ranged from 6.63 to 37.46 W/m$^2$ during winter 1998, and during 1999 it varied from 6.63 W/m$^2$ in the morning to $-4.29$ W/m$^2$ in the evening and during midday its value was about 120.46 W/m$^2$ (Figs. 2-3). A relatively lower daytime value of H is observed compared to LE during winters. Lower values of H in this season could be attributed to small surface-air temperature difference, and thus most of the $Q^*$ is available for transformation into LE reducing the H/Q$^*$ and G/Q$^*$ values. The ratios H/Q$^*$ and LE/Q$^*$ are positive and generally decline throughout the daytime, but in the morning and evening hours both show negative values. At around 07:00 hrs (morning) and 17:00 hrs (evening) LE/Q$^*$ values are higher than unity in winter 1998, whereas, during winter 1999 at around 08:00 hrs (morning) and immediately after sunset the values hops up after which they drift down to just below unity (Figs. 10-11) *(Grimmond and Oke, 1999).* However, both H and LE values are influenced by stomatal behavior and cloudiness, during the day time, which affects Q$^*$ *(Barradas et al., 1999).* During winter 1998, Q$^*$ dissipated by 38% and 62% by H and LE and the apportionment of H and LE accounted for about 34% and 51%, respectively in 1999 (Table 1). This indicates the higher value of evaporation and availability of more soil moisture during winter, since available energy utilized in heating the air (convection) is relatively lower. On a daily basis LE consumes about 11% more of the daily total Q$^*$ in winter 1998 as compared to 1999.

Similarly, during summer 1998 and 1999, H showed higher values amounting to about (140.28 W/m$^2$ and 169.63 W/m$^2$) at around 13:00 hrs, while the minimum values were about (−4.14 W/m$^2$ and −12.07 W/m$^2$) in the morning and in the evening the values were 6.56 W/m$^2$ and 4.07 W/m$^2$, respectively. LE ranged from −6.63 to 62.46 W/m$^2$ during summer 1998 and it was about −6.63 W/m$^2$ and 82.46 W/m$^2$ in the morning and midday hours, respectively during summer 1999 (Figs. 4–5). However, H remained positive throughout the day time (due to higher surface temperature relative to the air on both the summer seasons with fair weather conditions) with only small hour to hour changes in magnitude and sign during the morning and evening hours. Diurnal variation pattern of LE is similar to H except that values are lower. During summers (1998 and 1999) the heating up of the surface increased gradually due to an increase in magnitude of the Q$^*$. As a result, the difference between surface and air temperature gradually increased, enabling more energy to get dissipated into the air in the form of sensible heat. This reduced the radiant energy available for transformation into LE and G, resulting in the decrease in magnitude of LE/Q$^*$ and G/Q$^*$ during day time. It is evident from Figs. 12–13, which demonstrate positive values throughout the day time and negative in the morning and evening, though in both the summers LE/Q$^*$ showed positive values in the morning hours. Given the lower values of evaporation greatest interest centres on energy sharing between the G (conduction into the ground) and H (convection to the air). Nevertheless, fully 60% and 54% of $Q^*$ is utilized in heating the air of the lower atmosphere, compared to the 23% and 27% of $Q^*$ that is expended in evaporation in summer 1998 and 1999, respectively (Table 1). During summer 1998, about 6% more H is expended in convection to the lower atmosphere as compared to summer 1999.

Diurnal variation pattern of G is shown in Figs. 2, 3 and it ranged from $-5$ to 20 $W/m^2$ and $-5$ to 55 $W/m^2$, respectively during winters of 1998 and 1999. Similarly, during both the summers G showed pronounced diurnal variation (Figs. 4, 5). It ranged from $-5$ $W/m^2$ in the morning to about 60 $W/m^2$ in the noon hours during summer 1998. But during summer 1999 its values ranged from $-10$ $W/m^2$ to 70 $W/m^2$. G showed relatively higher values at noon hours during summer 1999 than 1998 (Figs. 2–5). This may be due to high apportioning of $Q^*$ to G during day time in summer 1999 and comparatively more exposure of bare soil in this season. The ratio $G/Q^*$ remains positive both day and night, except near sunrise (07:00 hrs) and sunset (17:00 hrs), when $Q^*$ suddenly changes sign. In both the winters (1998 and 1999) and summer 1998 in the morning and evening time $G/Q^*$ values are generally positive and less than unity, indicating that the G is smaller in magnitude than $Q^*$ and both are negative. Whereas, during summer 1999, $G/Q^*$ values are higher than unity in the morning and evening hours indicating magnitude of G is higher than $Q^*$ and it remained positive throughout the day, even in the morning and evening hours (Figs. 10–13). Only about 4% of $Q^*$ was transformed in to the conductive heat flux during winter 1998 due to lower apportionment of $Q^*$ to G, whereas, it was about 15% during winter 1999. The apportionment of $Q^*$ was about 18% and 20% for G during summer 1998 and 1999, respectively (Table 1).

The energy imbalance [$\Delta E = Q^* - (G+H+LE)$], following *Robinson and Henderson-Sellers (1999)* is computed on hourly basis and diurnal variation pattern of $\Delta E$ along with (G+H+LE) and $Q^*$ are shown in Figs. 6–9 for each season. Histograms show that during winter 1998 in the morning and evening hours, hourly values of $Q^*$ are negative and (G+H+LE) are positive. During day time magnitude of $Q^*$ dominating the (G+H+LE), and the corresponding diurnal variation pattern of $\Delta E$ is obvious (Fig. 6). During winter 1999 in the evening (20:00 hrs) both $Q^*$ and (G+H+LE) are negative and in the morning between (07:00 hrs) to (11:00 hrs) (G+H+LE) seems the dominating component. Higher negative energy imbalance amounting to about $-80$ W/m$^2$ at about 10:00 hrs is noticed since G+H+LE was higher by about 2 times than $Q^*$ (Fig. 7) at this time. During summers (1998 and 1999) diurnal variation pattern is similar to winters but in summer 1998, (G+H+LE) showed very small magnitude as compared to $Q^*$ (magnitude is negative) in the morning hours. Similarly, between 07:00 to 10:00 hrs, (G+H+LE) seems dominating $Q^*$, whereas, in the midday hours higher $Q^*$ is observed in this season. On the other hand in the evening (G+H+LE) values are higher than $Q^*$ and at around 10:00 hrs higher positive $\Delta$E is observed (Fig. 8). The diurnal course of variation during summer 1999 is similar to summer 1998 except with small hour to hour changes in $Q^*$, (G+H+LE) and $\Delta$E (Fig. 9).

The daily total (24–hourly sum) values of (H+LE+G) are higher than $Q^*$ in this site in all the seasons, that is, on daily basis $\Delta$E show the negative imbalance indicating the site to be energy sink. It is also noticed that (H+LE+G) are more than $Q^*$ by about 3.09% and 0.75% during winter 1998 and 1999 and 0.54% and 0.56% during summer 1998 and 1999, respectively. This indicates that during winters energy imbalance was comparatively higher than summers. On an average for all the seasons $\Delta$E is found to be about 0.84% that is $-12.55$ W/m$^2$ (Table 2). This could be due to the advection of energy from the immediate neighborhood or anthropogenically generated (from industrial and commercial areas) *(Oke, 1987; Padmanabhamurty, 1999a; 1999b; Offerle et al., 2006)*. As there was no surplus of energy the area acts as a heat sink.

The quality of energy balance components at BJP by determining the degree to which available energy ($Q^*$-G) is balanced by turbulent fluxes (H+LE), using linear regression analysis, following *Wilson and Baldocchi (2000)* is done. Best Linear fit between available energy ($Q^*$-G) and turbulence fluxes (H+LE) using linear regression analysis is conducted for average for all seasons and shown in Fig. 14. The line indicate the best linear fit of the data, and in the graph is included the equation of the line which show significant consistency ($R^2 = 0.98$) with slop = 0.79 and offset value of 11.39 W/m$^2$. Similarly, linear regressions for both the winters and summers (1998 and 1999) are also done and Table 3 summarizes the slop, offset and $R^2$ values demonstrating that turbulent fluxes are considerably correlated

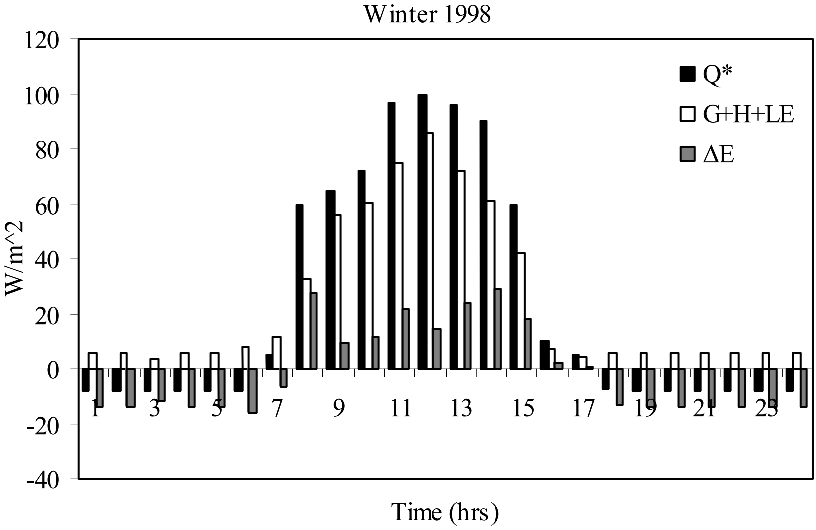

Fig. 6. Diurnal variation of Q$^*$, G+H+LE and ΔE in the Buddha Jayanti Park during winter 1998.

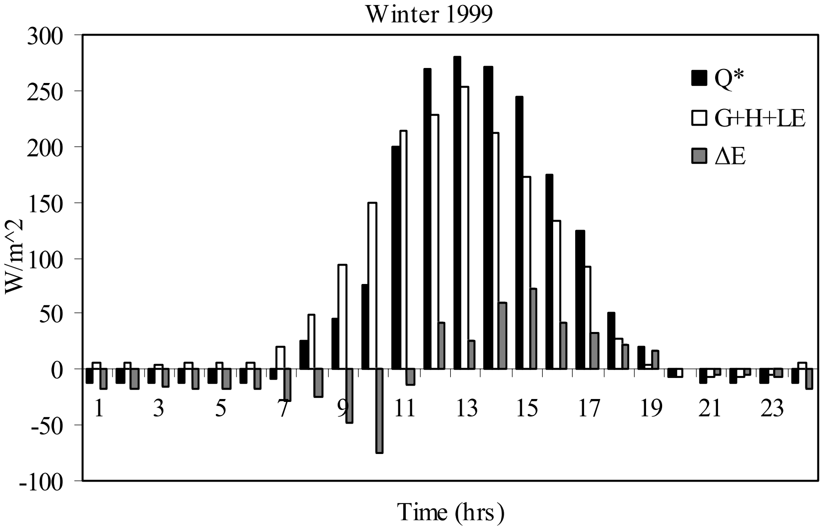

Fig. 7. Diurnal variation of Q$^*$, G+H+LE and ΔE in the Buddha Jayanti Park during winter 1999.

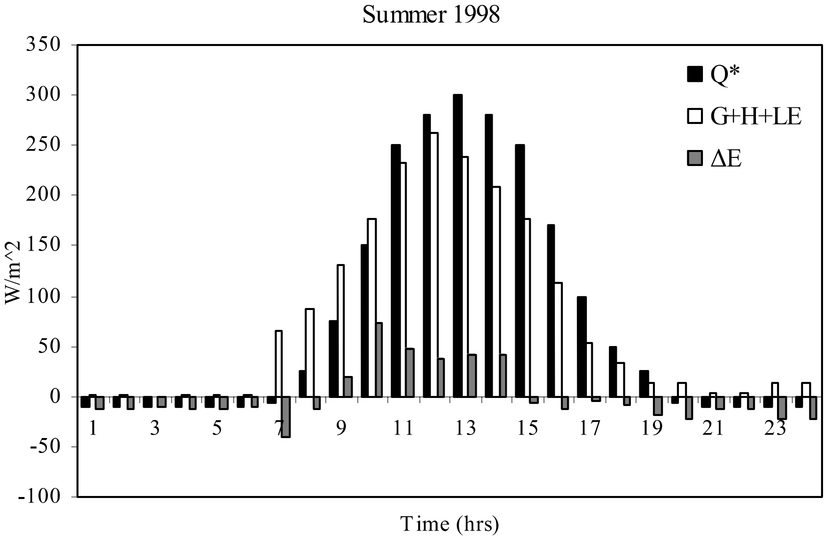

Fig. 8. Diurnal variation of Q*, G+H+LE and ΔE in the Buddha Jayanti Park during summer 1998.

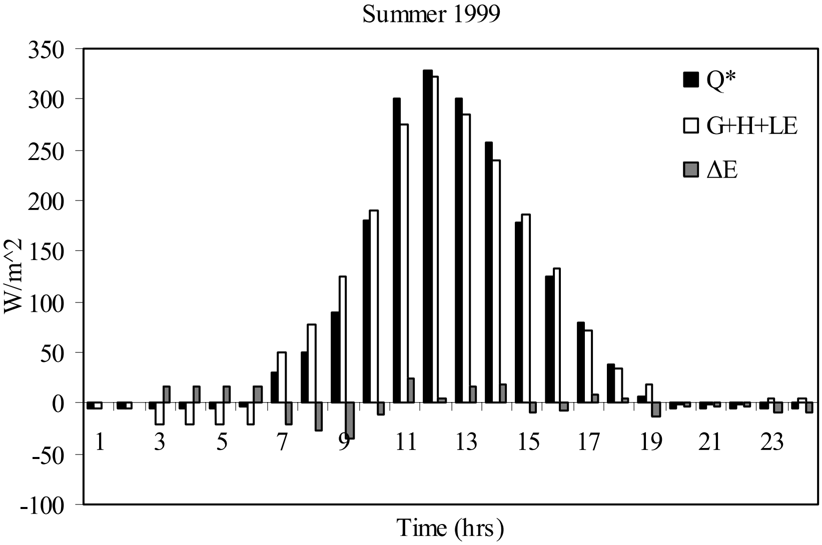

Fig. 9. Diurnal variation of Q*, G+H+LE and ΔE in the Buddha Jayanti Park during summer 1999.

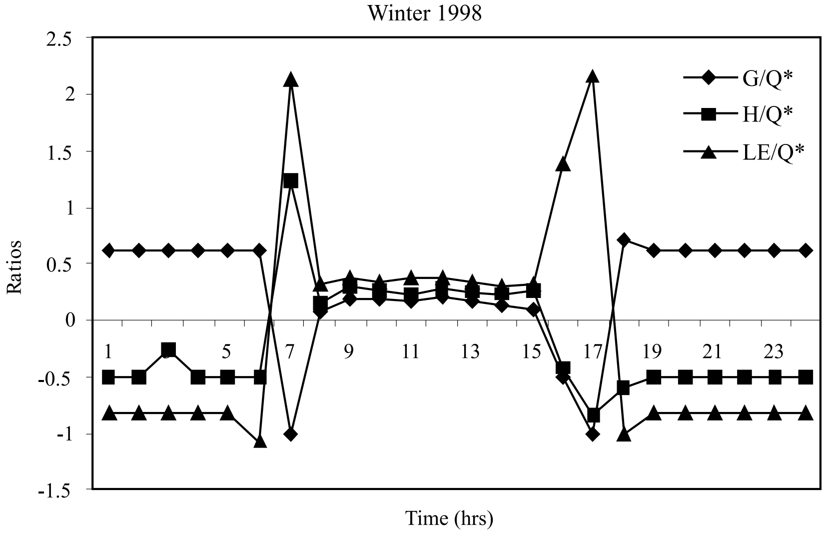

Fig. 10. Diurnal variation of ratios G/Q*, H/Q* and LE/Q* in the Buddha Jayanti Park during winter 1998.

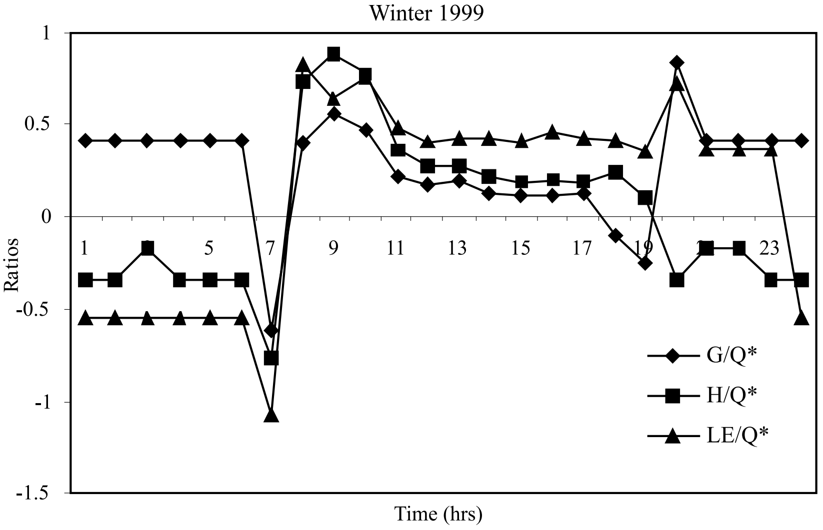

Fig. 11. Diurnal variation of ratios G/Q*, H/Q* and LE/Q* in the Buddha Jayanti Park during winter 1999.

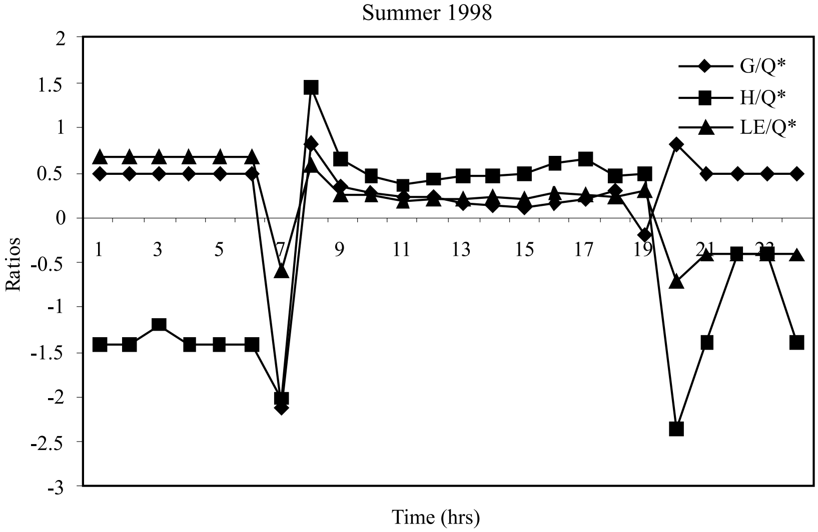

Fig. 12. Diurnal variation of ratios G/Q*, H/Q* and LE/Q* in the Buddha Jayanti Park during summer 1998.

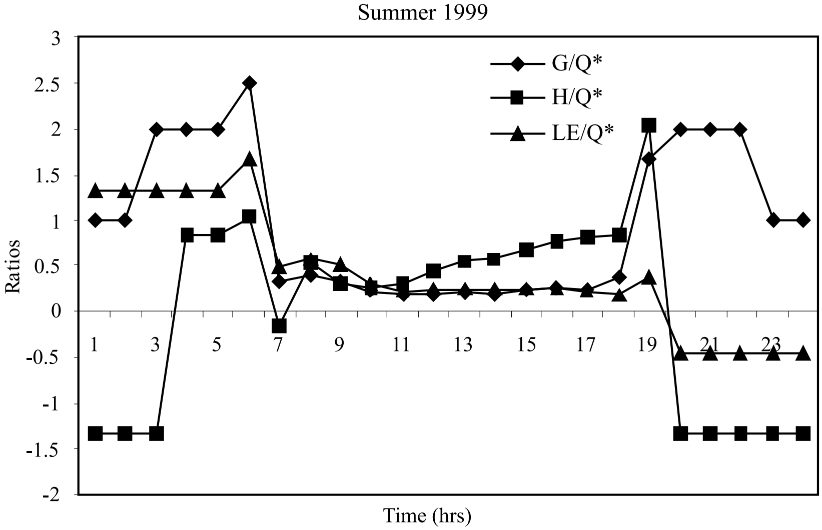

Fig. 13. Diurnal variation of ratios G/Q*, H/Q* and LE/Q* in the Buddha Jayanti Park during summer 1999.

Table 2. Daily Total values of $Q^*$, G+H+LE and $\Delta$E for different seasons and average for all seasons (W/m$^2$)

| Seasons | Winter 1998 | Winter 1999 | Summer 1998 | Summer 1999 | Avg for all seasons |
|---|---|---|---|---|---|
| Q* | 560.00 | 1648.00 | 1842.00 | 1909.50 | 1489.88 |
| G+H+LE | 577.33 | 1660.31 | 1851.90 | 1920.16 | 1502.43 |
| ΔE | -17.33 | -12.31 | -9.90 | -10.66 | -12.55 |
| ΔE % | 3.09 | 0.75 | 0.54 | 0.56 | 0.84 |

with available energy. However, summer 1998 showed higher $R^2$ (0.96) with offset values of 18.05 W/m$^2$ and slop = 0.72 than winter 1999 ($R^2 = 0.89$) with offset values of 16.59 W/m$^2$ and slop = 0.72. *Wilson et al. (2002)* and *Oliphant et al. (2004)* conducted similar analysis in their studies for energy balance closure.

A comparison of the partitioning of the energy balance components in the BJP with those at JNU (rural/vegetated) of Delhi City obtained by Bulk-aerodynamic approach *(Padmanabhamurty, 1994a)*, in urban area using eddy correlation method *(Tejeda-Martinez and Jauregui, 2005)* and suburban (vegetated) areas by Bowen ratio and energy balance method *(Barradas*

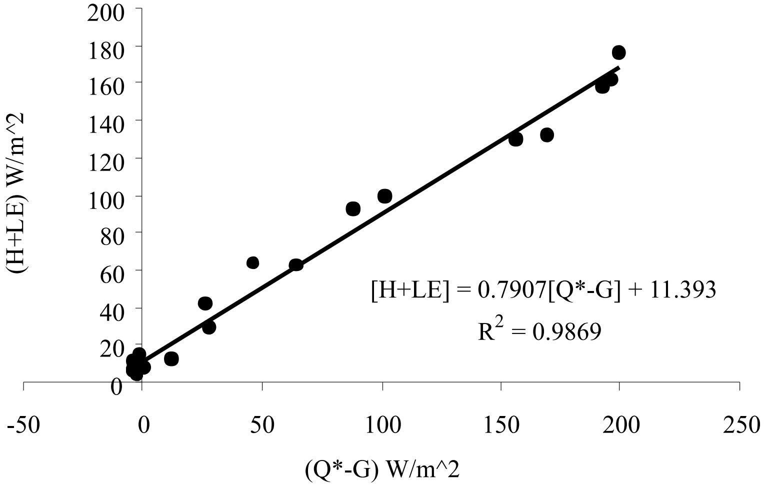

Fig. 14. Relation between turbulent heat fluxes and available energy at Budha Jayanti Park for averages for all the seasons (winters 1998 and 1999, summers 1998 and 1999).

Table 3. Linear regression slope, offset and coefficient of determination for Q*-G (independent variable) and H+LE (dependent variable) for different seasons and average for all seasons

| Seasons | Winter 1998 | Winter 1999 | Summer 1998 | Summer 1999 | Avg for all seasons |
|---|---|---|---|---|---|
| Slope | 0.52 | 0.72 | 0.72 | 0.90 | 0.79 |
| Offset | 10.90 | 16.59 | 18.05 | 6.76 | 11.39 |
| $R^2$ | 0.92 | 0.89 | 0.96 | 0.91 | 0.98 |

*et al., 1999)* of Mexico City, and in a Central European City by eddy correlation method *(Offerle et al., 2006)*, supports the hypothesis that BJP is similar to the rural/vegetated area during winter season, but to an urban site during summer season (Table 1). BJP may be drier than University Reserve, since the Bowen ratio ($\beta$) measured at BJP is higher (2.65 and 1.98) during summer (1998 and 1999) than that observed in University Reserve by *Barradas et al. (1999)* (1.92) during the dry season. On comparison of $\beta$ with winter season at BJP with that of wet season at University Reserve, it is observed that BJP is less humid than that of the University Reserve. Similar results were reported in earlier studies also in the rural/vegetated area in JNU *(Padmanabhamurty, 1994a)*, in Preparatory School No. 7, urban area of Mexico City *(Tejeda-Martinez and Jauregui, 2005)* and Central European City (urban area) *(Offerle et al., 2006)* (Table 1).

During the study period in winters LE > H whereas, in summers H > LE. The changes of LE and H from winter to summer season affect the thermal and moisture regimes and urban microclimate. Air temperature and air humidity would be higher and lower, during summer and vice-versa during winter seasons, respectively. These seasonal differences may be due to local/synoptic conditions, existence of vegetation and nature of substratum which affect the energy balance. The effect of Buddha Jayanti Park on the surroundings could be important since it acts as heat sink.

## 5. Conclusions

It is observed that Q* showed pronounced diurnal variation. Diurnal pattern of energy fluxes of LE, H and G and their partitioning showed distinct variation in both the seasons. This observed behavior of energy balance components in winters and summers could be attributed to the local/synoptic conditions and the nature of substratum, which influence the energy partitioning. However, higher apportionment of $Q^*$ in evaporating the surface moisture and the influence of vegetation in increasing the LE and the decrease of the Bowen ratio is noticed during winter seasons. During the summer seasons major portion of $Q^*$ is utilized in heating the air. The dependence of G on $Q^*$ in both the seasons is noticed.

This study is made over a portion of the southern ridge. Energy balance measurements over other parts of the ridge and the vegetated sites/urban parks should be conducted to assess the role of vegetation type present and the nature of substratum (e.g. water retention characteristics etc.) in urban microclimate in different seasons.

***Acknowledgments***. The authors wish to express their sincere thanks to Ministry of Science and Technology, Government of India for providing the financial assistance under the project entitle “Spatial and temporal variations of radiation, energy and moisture budgets in the boundary layer at Delhi (DST Ref. No.ES/048/319/95)” and School of Environmental Sciences, Jawaharlal Nehru University, New Delhi for making available the facilities for carrying out the work. Thanks are also due to Prof. C.V.S. Sastry, Nuclear Research Laboratory, Indian Agricultural Research Institute (ICAR), New Delhi for helping in instrumentation and providing valuable advice.

## References

Backstrom E., 2006: The surface energy balance and climate in an urban park. M. Sc. Thesis, Department of Earth Sciences, Geotryckeriet, Uppsala University, Uppsala, 39 p.

Baldocchi D., Falge E., Gu L., Olson R., Hollinger D., Running S., Anthoni P., Bernhofer C., Davis K., Evans R., Fuentes J., Goldstein A., Katul G., Law B., Lee X., Malhi Y., Meyers T., Munger W., Oechel W., Paw U. K. T., Pilegaard K., Schmid H. P., Christen A., Vogt R., Rotach M., Parlow E., 2002: First results from BUBBLE II: Partioning of turbulent heat fluxes over urban surfaces. Preprints, Fourth Symp. on the Urban Environment, Norfolk, VA, Amer. Meteor. Soc., 137–138.

Barradas V. L., 1991: Air temperature and humidity and human comfort index of some city parks of Mexico City. Int. J. Biometeorol., **35**, 24–28.

Barradas V. L., Tejeda-Martinez A., Jauregui E., 1999: Energy balance measurement in a suburban vegetated area in Mexico City. Atmospheric Environment, **33**, 4109–4113.

Bolle H.-J. et al., 1993: EFEDA: European Field Experiment in a Desertification-threatened Area. Ann. Geophys., **11**, 173–189.

Budyko M. I., 1981: The Earth's Climate: Past, Present and Future, First Eds. Academic Press, New York, 356 p.

Cao Z., Ma J., 2004: An Application of the Variational Method to Computation of Sensible Heat Flux over a Deciduous Forest. J. Appl. Meteorology, **44**, 144–152.

Census of India, 2001: A cartographic view (Govt. of India), 225 p.

Christen A., Vogt R., Rotach M. W., Parlow E., 2002: First results from BUBBLE II: partitioning of turbulent heat fluxes over urban surfaces, Preprints, Fourth Symp. on the urban environment, 20–24 May 2002, Norfolk, Virginia. Amer. Meteor. Soc., 105–106.

Cleugh H. A., Oke T. R., 1986: Suburban–rural energy balance comparisons in summer for Vancouver, B. C., Bound-Layer Meteor., **36**, 351–369.

Climatological tables of observatory of India (1953-1980) India Meteorological Department (1998).

Cros B., Durand P., Cachier H., Drobinski P., Fréjafon E., Kottmeier C., Perros P. E., Ponche J.-L., Robin D., Said F., Toupance G., Wortham H., 2004: The ESCOMPTE program: An overview. Atmos. Res., **69**, 241–279.

Centre for Science and Environment (CSE), New Delhi, Report. (`http://www.rainwaterharvesting.org/index_files/geology.htm`).

Das Y., 2002: Spatial and temporal distribution of radiation/energy/moisture budgets over Delhi. Ph.D. Thesis, Berhampur University, Berhampur, India, 125 p.

Delhi Development Report, 2006: Oxford University Press, Delhi Govt., 134 p.

Greening Delhi Action Plan 2005-2006, Department of Forests and Wildlife, Govt. of NCT of Delhi, 62 p.

Grimmond C. S. B., 2006: Progress in measuring and observing the urban atmosphere. Theor. Appl. Climatol., **84**, 3–22.

Grimmond C. S. B., Oke T. R., 2002a: Heat fluxes and stability in cities, European COST (Co-operation in the Field of Scientific and Technical Research) 715 Surface Energy Balance in Urban Areas, Proc. COST-715 Expert Meeting, Antwerp, Belgium, 12 April 2000. European Commission, Report EUR 19447, 16–30.

Grimmond C. S. B., Oke T. R., 2002b: Turbulent heat fluxes at urban area: Observation and a local-scale urban meteorological parameterization scheme (LUMPS). J. Appl. Meteorology, **41**, 792–810.

Grimmond C. S. B., Oke T. R., 1999: Heat storage in urban areas: local-scale observations and evaluation of a simple model. J. Appl. Meteorology, **38**, 7, 922–940.

Hakansson L., Peters R. H., 1995: Predictive Limnology – methods for predictive modelling. SPB Academic Publishing, Amsterdam.

Jochum M. A. O., Hendrik A. R., De Bruin, Holtslag A. A. M., Belmonte A. C., 2005: Area-averaged surface Fluxes in a Semiarid Region with Partly Irrigated Land: Lessons Learned from EFEDA. Jour. Appl. Meteor. and Climatology, **45**, 856–874.

Jones H. G., 1992: Plants and microclimate: A quantitative approach to environmental plant physiology. Cambridge University Press, Cambridge, 428 p.

Lagouarde J. P., Irvine M., Bonnefond J. M., Grimmond C. S. B., Long N., Oke T. R., Salmond J., Offerle B., 2006: Monitoring the sensible heat flux over urban areas using large aperture scintillometry: case study of Marseille city during the ESCOMPTE experiment. Boundary Layer Meteorology, **118**, 3, 449–476.

Lemonsu A., Grimmond C. S. B., Masson V., 2004: Modeling the Surface Energy Balance of the Core of an Old Mediterranean City: Marseille. Jour. Appl. Meteorology, **43**, 2, 312–327.

McCaughey J. H., Saxton W. L., 1988: Energy balance storage terms in a mixed forest. Agric. For. Meteorol., **44**, 1–18.

Mestayer P., Durand P., Augustin P., Bastin S., Bonnefond J. M., Bénech B., Campistron B., Coppalle A., Delbarre H., Dousset B., Drobinsk P., Druilhet A., Fréjafon E., Grimmond C. S. B., Groleau D., Irvine M., Kergomard C., Kermadi S., Lagouarde J. P., Lemonsu A., Lohou F., Long N., Masson V., Moppert C., Noilhan J., Offerle B., Oke T. R., Pigeon G., Puygrenier V., Roberts S., Rosant J. M., Saïd F., Salmond J., Talbaut M., Voogt J., 2005: The urban boundary layer field experiment over Marseille UBL/CLU-ESCOMPTE: Experimental Set-up and First Results. Boundary Layer Meteorology, **114**, 2, 315–365.

Ministry of Environment and Forest (Forest survey of India) (MoEF (FSI)) (2003) (`http://fsi.nic.in/index.htm`).

Ministry of Environment and Forest (`http://www.envfo.nic.in`), Govt. of India, 1999.

Munn R. E., 1966: Descriptive Micrometeorology, Academic Press, New York.

Offerle B., Grimmond C. S. B., Fortuniak K., Klysik K., Oke T. R., 2006: Temporal variations in heat fluxes over a Central European city centre. Theor. Appl. Climatol., **84**, 103–115.

Oke T. R., 1987: Boundary Layer Climates. John Wiley and Sons, New York, 450 p.

Oke T. R., Spronken-Smith R. A., Jauregui E., Grimmond C. S. B., 1999: The energy balance of central Mexico City during the dry seasons. Atmospheric Environment, **33**, 3919–3930.

Oke T. R., Zeuner G., Jauregui E., 1992: The surface energy balance in Mexico City. Atmospheric Environment, **26B**, 4, 433–444.

Oliphant A. J., Grimmond C. S. B., Zutter H. N., Schmid H. P., Su H. B., Scott S. L., Offerle B., Randolph J. C., Ehman J., 2004: Heat storage and energy balance fluxes for a temperate deciduous forest. Agriculture and Forest Meteorology, **126**, 185–201.

Padmanabhamurty B., 1984: Some aspects of the urban climates of India, Proc. of Tech. Conf. on Urban Climatology and its applications with special regard to tropical areas (WMO–652), 136–165.

Padmanabhamurty B., 1990/91: Microclimate in tropical urban complexes, Energy and buildings, **15-16**, 83–92.

Padmanabhamurty B., 1990a: Role of microclimate in town planning and landscape architecture. Vayu Mandal, January-June, 38–43.

Padmanabhamurty B., 1990b: Urban climate research in India. In: Proceeding of first Int. Symp. on Urban Climate, Air Pollution and Planning (Guadalajara Mexico), 75–79.

Padmanabhamurty B., 1994a: Urban–rural energy and moisture balance studies over Delhi, Final Report, DST Project. Ref. No. ES/63/018865 (Govt. of India), 102 p.

Padmanabhamurty B., 1994b: Tropical urban climate - A scientific challenge, Rep. of Tech. Conf. on Trop Urban Climate (WCASP-30 WMO/TD No. 647 WMO) 449–470.

Padmanabhamurty B., 1999a: Hot cities in a hot world. Keynote lecture at ICB_IUCC '99, Sydney, Australia, (WMO) Nov. 8-12.

Padmanabhamurty B., 1999b: Spatial and temporal variations of radiation, energy and moisture budgets in the boundary layer at Delhi. Final Report on DST Project. Ref. No. ES/48/319/95 (Govt. of India), 49 p.

Piringer M., Grimmond C. S. B., Joffre S. M., Mestayer P., Middleton D. R., Rotach M. W., Baklanov A., De Ridder K., Ferreira J., Guilloteau E., Karppinen A., Martilli A., Masson V., Tombrou M., 2002: Investigating the surface energy balance in urban areas – recent advances and future needs. Water, Air and Soil Pollution: Focus 2 (5-6), 1–16.

Raman S., Niyogi D. S., Prabhu A., Ameenullah S., Nagaraj S. T., Udai Kumar, Jayanna, S., 1998: VEBEX: Vegetation and surface energy balance experiment for the tropics. Proceedings of Earth and Planetary Sciences (Indian Acad. Sci.), **107**, 97–105.

Robinson P. J., Henderson-Sellers A., 1999: Contemporary Climatology, Pearson Education Limited, Longman, $2^{\text{nd}}$ Edn., 317 p.

Rotach M., 2002: Overview on the Basel Urban Boundary Layer Experiment—BUBBLE, Preprints, Fourth Symp. on the Urban Environment, Norfolk, VA. Amer. Meteor. Soc., 25–26.

Rotach M. W., Vogt R., Bernhofer C., Batchvarova E., Christen A., Clappier A., Feddersen B., Gryning S.-E., Mayer H., Mitev V., Oke T. R., Parlow E., Richner H., Roth M., Roulet Y.-A., Ruffieux D., Salmond J., Schatzmann M., Voogt J. A., 2005: BUBBLE – an urban boundary layer project. Theor. Appl. Climatol., **81**, 3-4, 231–261.

Sathapathy K. L., 1998: Urban – rural energy and moisture balance studies over Delhi, Ph.D Thesis, Berhampur University, Berhampur, India, 123 p.

Saxena S., Pillai J. S., Murthy B. S., 1996: Energy balance at land-surface interface. Mausam, **44**, 2, 115–124.

Su H. B., Schmid H. P., Grimmond C. S. B., Vogel C. S., Oliphant A. J., 2004: Spectral characteristics and correction of long-term eddy covariance measurements over two mixed hardwood forests in non-flat terrain. Boundary-Layer Meteorology, **110**, 213–253.

Spronken-Smith R. A., Oke T. R., Lowry W. P., 2000: Advection and the surface energy balance across an irrigated urban park. Inter. Jour. Climatol., **20**, 1033–1047.

Tejeda-Martinez A., Jauregui E., 2005: Surface energy balance Measurements in the Mexico City region: a review. Atmosfera, 1–23.

Thorsson S., Eliassons I., 2003: An intra-urban thermal breeze in Gotenborg, Sweden. Theor. Appl. Climatol., **75**, 93–104.

Thorsson S., Lindqvist M., Lindqvist S., 2004: Thermal bioclimatic conditions and patterns of behaviour in an urban park in Göteborg, Sweden. Int. J. Biometeorol., **48**, 149–156.

Upmanis H., 1999: Influence of Parks on Local Climate. Ph.D. Thesis, Earth Sciences Centre, Göteborg University A43, Gothenburg.

Upmanis H., Eliasson I., Lindqvist S., 1998: The influence of green areas on nocturnal temperatures in a high latitude city (Goteborg, Sweden). Int. J. Climatol., **18**, 681–700.

Vernekar K. G., Sinha S., Sadani L. K., Sivaramakrishnan S., Parasnis S. S., Mohan B., Saxena S., Dharmaraj T., Patil M. N., Pillai J. S. , Murthy B. S., Debaje S. B., Bagavathsingh A., 2003: An Overview Of The Land Surface Processes Experiment (LASPEX) Over A Semi-Arid Region Of India. Boundary - Layer Meteorology, **106**, 3, 561–572.

Webb E. K., Pearman G. I., Leuning R., 1980: Correction of flux measurements for density effects due to heat and water vapor transfer. Quarterly J. of Royal Met. Soc., **106**, 85–100.

Wilson K. B., Goldstein A., Falge E., Aubinet M., Baldocchi D., Berbigier P., Bernhofer C., Ceulemans R., Dolman H., Field C., Grelle A., Ibrom A., Law B. E., Kowalski A., Meyers T., Moncrieff J., Monson R., Oechel W., Tenhunen J., Valentini R., Verma S., 2002: Energy balance closure at FLUXNET sites. Agric. For. Meteorol., **113**, 223–243.

Wilson K. B., Baldocchi D. D., 2000: Seasonal and inter-annual variability of energy fluxes over a broadleaved temperature deciduous forest in North America. Agric. For. Meteorol., **100**, 1–8.